

## Book review

# Light, sight, and quanta

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*The Optics of Life — A Biologist's Guide to Light in Nature*

Sönke Johnsen

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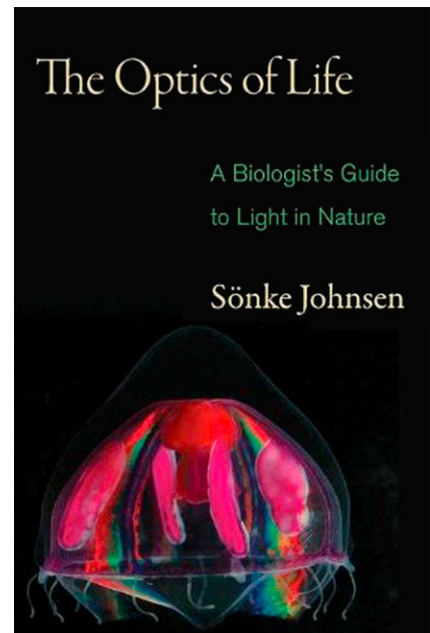
Ever since the rival corpuscular and wave theories of light, developed by Newton and Huygens in the 17<sup>th</sup> century, light has always been maddeningly difficult stuff to understand, and since the advent of quantum theory during the 20<sup>th</sup> century, the problems of conceptualising it have, if anything, worsened. Richard Feynman, in *QED* [1], is quite blunt about this: “The theory of quantum electrodynamics describes Nature as absurd from the point of view of common sense”. But he adds, “And it agrees fully with experiment”. For those of us who learnt our optics before 1985, when *QED* was published, the new world of photons and probability waves is unsettling. The old certainties of rays and waves are done away with, and all optical phenomena end up with the scattering of photons from the outer electrons of atoms, and their probabilistic behaviour thereafter. In this book Johnsen steers a careful course between the old and the new optics, using whichever form of description is most useful for the phenomenon he is describing. His style is fluent, witty and a pleasure to read, in spite of the trickiness of some of the subject matter.

Sönke Johnsen is primarily a marine biologist. His book is about the behaviour of light on land and in the sea, and is intended as a guide for modern biologists whose work involves understanding and measuring light in the environment. It covers all the ways in which light interacts with matter, and the observable phenomena that arise from these interactions. There are chapters on emission, absorption, scattering, fluorescence and polarization. He does not deal with the optics of eyes, which are adequately covered elsewhere [2]. There is plenty of modern physics — not so hard that you need a physics degree, but you will not make headway without

a decent science background. (Sönke himself says he was bored by physics in college and switched to maths, but clearly what was already there stuck [3]). The book is by no means all theory; there are a host of examples, many from his own studies, of the ways in which animals make use of the different kinds of interactions between light and matter.

The book begins with the measurement of light and a discussion of units. Two quite different ways of measuring light developed over the years. Radiometric systems measure light in terms of universal units: watts or photons per second. The measurements differ depending on whether a surface is emitting (radiance) or accepting light (irradiance), and both depend on the spectral composition of the light. Photometric units, on the other hand, are based on the human perception of light (candela, lux, and a very odd collection of other units used historically by lighting engineers). These units are biased by the human spectral sensitivity curve and are of little value when dealing with non-human vision. Johnsen gives a caveat at the end of the chapter, “Do not use photometric units... Avoid even reading about them”. Later in the book there is a chapter specifically on the measurement of light (Chapter 9), which gives practical advice on spectroscopy, and methods for measuring reflectance, transmittance, radiance and scattering.

Much of the book is taken up in various ways with visibility, particularly the visibility of objects in the sea. The sun and bioluminescence are the main sources of light for vision. On land, few animals make their own light, but, in the ocean, bioluminescence becomes increasingly important, as light from the surface attenuates to effectively nothing by 1000 metres down. In fact, it is something of a miracle that sunlight penetrates the sea at all — water is opaque to electromagnetic radiation with wavelengths below 200 nm and above 1000 nm (page 35), so that the window of transparency just encompasses the visible range (350–750 nm). Even within this range, it is only blue light (~480 nm) that penetrates to any great depth, making the mid-water world essentially monochromatic. Since food is scarce and there is nowhere to hide in the open ocean, detecting prey and avoiding detection are the keys to mid-water survival. Predators tend to have large upward-pointing eyes to spot the silhouettes of creatures above them, and potential prey typically disguise



their lower surfaces with photophores that they use to match the downwelling light that their bodies are blocking. Some fish, crustaceans and squid can do this over a thousand-fold intensity range. Luminescence at these depths has many other uses — twelve are listed on page 63, and include various ways of distracting predators, using lures to attract prey, and headlamps to illuminate prey in the water ahead. Dragonfish (Stomiidae), uniquely, have red photophores (and red-sensitive visual pigments), apparently to illuminate the red crustaceans, whose pigment makes them invisible to all other blue-sensitive predators.

Scattered light is another important factor that determines how far away one animal can see another. When viewing under water, some light from an object is scattered out of the beam either by small particles or, in clear water, by the water molecules themselves. Equally, veiling light from the background gets scattered into the beam, so that at some point the object and the background have the same luminance, and the object becomes invisible. I recall being surprised by the way a white object (a Secchi disc) simply disappeared at a particular depth in turbid water. On land this happens in fog, where the small particle size (compared to rain) makes it a potent scatterer. Objects do not just become faint — they vanish. Chapter 5 provides a useful account of the way that scattering varies with particle size, and the ways that Rayleigh (small particles), Mie (larger particles)

and others developed quantitative ways of coping, well before the photon had been conceived. Photon scattering can now accommodate all scattering phenomena, but as Johnsen points out, it is computationally messy.

Chapter six is a tough one for those of us who belong to the rays and waves tradition. It includes transparency, reflection and refraction but is titled simply 'Scattering with interference'. We are in quantal territory here. The first paragraph is wonderfully uncompromising, and I can't resist quoting it in full:

"Light does not bend in a lens, it doesn't bounce off the surface of glass, and it doesn't spread out after passing through a small hole. It doesn't even travel in a straight line. The happiest day of my scientific life came when I read Feynman's QED and learned that refraction, reflection, and diffraction — things I had known since the fifth grade — were all lies. More accurately they are illusions. It appears that light bends, bounces and spreads out. The illusions are so good that you can base solid mathematical predictions on them, but careful thought and further experiments show that more is going on."

In classical optics, electromagnetic waves travel through space at the speed of light and interfere with each other when they meet to add their amplitudes or cancel each other, depending on their phase relationships. In quantum optics, all that can be observed is the emission or absorption of a photon. Between these events the wave in transit has phase and is capable of interference, but cannot be located. It can only be described in terms of the probability that it will encounter an atomic electron, and then release all its unitary energy. For someone with a basically Newtonian mindset, the bizarreness of this formulation comes from the idea that the energy of the photon somehow dissipates into a probability cloud, and then gets itself together again for an interaction with matter. It seems I am not alone in this failure of imagination. But, having admitted this failing, it has to be said that quantum optics provides an accurate and apparently complete account of all the well-known optical phenomena — reflection, refraction, diffraction and so on. The reader should consult Feynman [1] to be convinced of this. In his classic textbook [4], Rodney Loudon tells us:

"It is never the photons themselves that interfere, one with another, but rather the probability amplitudes that describe their propagation from the input to the output." Fortunately, most of the formalisms that describe the interference phenomena that form the basis of classical optics also hold for the probability waves of quantum optics.

I will give a single example of the jolt I received from the new photon thinking. I have worked on multilayer reflectors (butterfly wings, fish scales) on and off since about 1970. In a thin film some light is reflected from the upper surface and some from the lower surface, and these two wavefronts interfere, constructively or destructively, to produce a high reflectance for some wavelengths and low for others. This, I now learn, is wrong. What really happens is that photons are scattered from molecules *throughout* the film, some continue forwards, delaying the phase of the continuing beam (refraction), and some backwards (reflection). The surfaces themselves are unimportant, as is explained by Feynman [1] on pages 103–109. It turns out that the many probability amplitude vectors from the backscattered photons add up to give a resultant that can be resolved into two vectors that *look as though* they have come from the upper and lower surfaces. And the mathematics is magically the same.

In his last chapter, Johnsen gets into what he describes earlier as the truly weird parts of quantum mechanics that are not relevant to biology. Quantum entanglement is a phenomenon in which two photons emitted simultaneously from the same crystal appear to communicate with each other over vast distances. As Johnsen says: "If nothing else about light bothers you, quantum entanglement really should". Enough. I am grateful to this book for forcing me to come to terms with a number of aspects of light that I had been delinquent enough to ignore, and in a way that was a pleasure — like a long walk in hilly country.

#### References

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## Q & A

### David Sumpter

*David Sumpter was educated at Woodmill High School, Dunfermline and the University of Edinburgh, before completing a PhD in applied mathematics at the University of Manchester. He has since worked at both mathematics and biology departments in Oxford and Umeå. He was appointed professor in Uppsala, Sweden in 2007. His research is on 'Collective Animal Behaviour', which is also the title of a book he published last year.*

**Were you interested in biology from an early age?** No, not at all. When I was nine years old, my parents bought a home computer. I became fascinated with programming and would spend hours typing in programs from magazines and trying to write my own code. At that time, I think I saw computers and biology as opposites. At school, biology was about dredging in ponds and writing long lists of the names of all the messy stuff you found there. Computers were structured. You could control them and when you learnt something it was logical and made sense in other contexts. When I was 13 I dropped biology studies at school and concentrated on the other sciences and mathematics instead.

**So when did your interest in biology start?** When I finished my undergraduate degree in computer science and statistics I wanted to apply these skills to making mathematical models and computer simulations of 'something'. I didn't mind too much what this something was.

With this in mind, in the first few weeks of my PhD studies, I read Tom Seeley's book *'Wisdom of the Hive: Social Physiology of Honey Bee Colonies'*. Seeley had set out to disentangle the inner workings of the honey bee colony. He didn't just want to describe the behavior of the bees, but to get to the bottom of a set of logical processes and interactions. For example, his study of how bees regulate and balance the in-flow of water, nectar and pollen in to the hive, led him to think in general